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Cavitation and Nuclei

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Contrary to the general impression, water and other common liquids, when pure, have high tensile strength. Cavitation would be impossible at the highest velocities currently encountered. In practice all liquids appear to cavitate as soon as the pressure tends to drop below the vapor pressure, thus implying that liquids have no tensile strength. This discrepancy is explained by the presence of "weak spots" whose characteristics have as yet only been inferred.

This paper presents the results of an experimental investigation of the weak spots present in ordinary water. The results are consistent with the model of the nucleus proposed by Harvey, but are apparently inconsistent with other models currently found in the literature.

After summarizing the results of the experimental program, the paper concludes with a series of implications concerning the engineering significance of the nuclei in industrial liquids.

An experimental knowledge of the property of liquids is universal. From the day of our birth we bathe in liquids, drink liquids, see uncounted numbers of liquid droplets fall as rain, even our own bodies consist largely of liquids. Hence every young scientist or engineer starts his education with a good empirical knowledge of the properties of liquids. Since this knowledge is built up of so many unrelated experiences, it is apt to be present more often as an intuitive feeling rather than as an explicit collection of facts. This intuition generally colors our approach to technical problems related to liquids, and the problem of cavitation is certainly no exception.

The formation of a cavity in a liquid obviously involves a rupture of the liquid, but intuition says that a liquid has no rupture strength as it is always spilling, splashing and bouncing around, dividing and recombining, with little or no apparent application of force. Thus obviously a liquid will rupture and form a cavity at any place within the liquid at which an infinitesimal tension develops. Unfortunately, there are occasional natural examples which cast a shadow on this intuitive feeling that liquids cannot withstand any tensile stress. Trees draw sap up from the ground to far greater heights than can be explained unless the sap can withstand a tension. Technical individuals who work intimately with the cavitation process sooner or later encounter cases which can be understood only on the basis that the liquid is able to withstand a tension, at least for a short time.

It is of practical importance to designers and users of hydraulic equipment to have a clear knowledge of all physical properties of liquids that may affect the cavitation process. Obviously the cavitation-free zones of operation could be greatly extended if liquids could be made to stand appreciable tensions. Unfortunately, our present experience indicates that it is not feasible to do this, at least for aqueous liquids. On the other hand, there is some indirect evidence to show that even natural waters may vary significantly in their ability to withstand momentary tensions. These variations may occur between water derived from different sources, or the same water supply may have different properties at different times of the year. Another field in which knowledge of these physical characteristics of the liquid is important is in model testing of the cavitation characteristics of hydraulic equipment, such as pumps and turbines. These are some of the motivating facts for the investigations which will be discussed.

To understand the nature of these investigations, it is necessary to review some of the known physical facts about the effective tensile strength of liquids. Based on their physical structure, liquids should have very high tensile strengths—of the order of tens or hundreds of thousands of pounds per square inch. If real liquids actually exhibited such strengths, cavitation would be unknown. However, it is common experience that ordinary liquids usually cavitate whenever the local pressure reaches the vapor pressure. Since this is the point at which there is no longer an external force to hold the liquid together, it shows that these liquids have no effective tensile strength. The obvious explanation of this great discrepancy is that ordinary liquids always contain impurities which produce weak spots that rupture or tear at vanishingly small tensions, thus producing cavities. Liquids may contain many types of impurities, only a few of which could be expected to produce weak spots. Since the weak spots are physical in nature, it would appear that the physical characteristics of the impurities would be of prime importance.

The physical state of dissolved impurity is quite different from the undissolved one. The theory of solutions indicates that a dissolved impurity should have very little effect on the tensile strength of the base liquid and thus this class of impurities can be eliminated from consideration. This leaves undissolved solids, immiscible liquids, and free gas as the possible sources of weak spots in ordinary liquids. With undissolved solids and immiscible liquids, the interface between the impurity and the base liquid is a potential source of the weak spot since the tensile strength of the impurities is of a higher order of magnitude. Immiscible liquids do not appear to be a primary source of weak spots. In the first place, they are not universally present in common liquids. In the second place, experiments performed by Weyl and Marboe (12)[2] demonstrated that the interface between immiscible liquids is not weak enough to explain the observed lack of effective tensile strength of normal liquids.

The tensile strength of the interface between a solid impurity and the liquid depends upon the degree of wetting of the solid by the liquid. There is ample experimental evidence to show that with a high degree of wetting the adhesive force across the interface is very high, and even for a low degree of wetting it is probably higher than the effective tensile strengths observed in normal liquids. This reasoning reduces the range of impurities responsible for the weak spots in liquids to undissolved gases, and unwetted, that is, hydrophobic solids.

In considering the probability that either of these two types of impurities is responsible for the weak spots in ordinary liquids, another experimental fact must be considered. Clear water, or even commercial distilled water, cavitates with very little, if any, sign of tensile strength. This means that any undissolved impurities must exist in very tiny units. Otherwise, the liquid would appear cloudy. The effect of a tiny hydrophobic solid particle on the tensile strength of a liquid is not too clear. Among other things, it would depend upon the size and shape of the particle.

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[2] Numbers in parentheses refer to the Bibliography at the end of the paper.

Certainly the interfacial tension of the liquid would have to be taken into account. However, the resistance to opening a cavity at the interface would certainly be less than that in the pure liquid. Obviously, the tiny gas bubbles constitute weak spots in the liquid. For the common liquids, and especially for water, the only readily available source of gas is the atmosphere, and the atmospheric gases are relatively soluble. Thus it is difficult to explain the continuing existence of a very small free bubble in a body of liquid, since the surface tension forces should be great enough to increase the pressure within the bubble sufficiently to cause it to dissolve completely.

All of this discussion can be summed up very tersely by saying that liquids should not cavitate, but they do. Furthermore, the only acceptable explanation for the weak spots that are necessary to permit cavitation is that based on the presence of impurities. In recognition of this, these weak spots are commonly called nuclei, although their existence is still wholly inferential. One of the few tenable concepts of the construction of a nucleus is due to Harvey (8). His model of a nucleus is that it consists of a host which is a solid hydrophobic particle which has a re-entrant crack in its surface that is filled with undissolved gas. This gas is the active part of the nucleus, that is, the weak spot in the liquid. Since the particle surface is hydrophobic, the surface of the liquid will be convex toward the gas. Hence the surface tension will tend to keep the gas pressure low rather than high. Consequently, the gas will not dissolve. Harvey made some experiments which showed that this concept is consistent with the physical facts. He reasoned that such nuclei could be destroyed by applying hydrostatic pressures which, if high enough, would force the liquid up into the crack against the force of surface tension and cause the gas to dissolve, thus eliminating the weak spot. The experiments carried out by the author are elaborations of Harvey's original tests. Their objective was not only to obtain a more quantitative check upon the tenability of such a hypothetical nucleus, but also to explore in detail the characteristics of water before and after a wide variety of pressure treatments. It was hoped in this manner some light would be shed on some of the observed inconsistencies in the cavitation performance of hydraulic equipment.

The general plan of all experiments is the same: To compare the physical characteristics of unpressurized water with that of similar samples which have been pressurized. These experiments cover relatively wide ranges of intensity and duration of the pressurizing treatment. The physical characteristic investigated is the development of cavities within the body of the sample. Both static and dynamic tests were made. The static tests were of two kinds: The first was the determination of the boiling point at atmospheric pressure of a previously pressurized sample of water as compared to that of an unpressurized sample. A boiling point in excess of the equilibrium temperature at atmospheric pressure indicates that the liquid has an effective tensile strength. This tensile strength is the difference between the vapor pressure at the boiling temperature and the vapor pressure corresponding to the local atmospheric pressure. During the making of the boiling-point measurements, observations were also taken of the type of boiling and the location of the initial cavities within the body of the liquid.

In the second type of static test the previously pressurized sample was heated in a water-vapor-filled pressure-release chamber until a predetermined pressure and temperature was reached. The chamber pressure was then released at a predetermined rate until cavities appeared in the body of the sample. The effective tension required to produce the first cavity in this test was the difference between the chamber pressure at the beginning of the test and that at the appearance of the first cavity.

The dynamic test was completely different. A glass venturi tube having a large upstream reservoir section was cleaned and filled with water to be tested, and the entire assembly was then pressurized. After this treatment, the venturi was placed in special apparatus and flow was induced by sudden application of air pressure. By suitably adjusting this pressure, the pressure in the throat of the venturi could be controlled. In this manner tensions of several atmospheres could be obtained with relatively low drive pressures. In this test the cavity develops under conditions comparable to that in hydraulic equipment in general. Variations in pressure are produced by changes in the velocity of the flow.

Description of Equipment

The pressurizing chamber and auxiliary equipment is shown in Fig. 1. The pressurizing chamber is $2^5/_8$ in. ID and has a usable length of approximately 30 in. The pressure is produced by a ram in the lower end of the chamber which is driven by a low-pressure hydraulic cylinder that forms the base of the chamber. This low pressure cylinder is a part of a closed hydraulic system that includes a standard gear pump with associated control valves and reservoir. The area ratio of the low-to-high pressure piston is about 33 to 1. Thus working pressures up to 30,000 psi are obtained in the chamber from a maximum operating pressure of 1000 psi in the auxiliary system. A dial gage which measures the change in length of the high pressure cylinder is used to indicate the level of pressurization. Access to the chamber is provided by a plug with an unsupported-area seal. This plug and its holding pin can be seen on the left side of Fig. 1, sitting on top of the pressurization chamber.

Static Test Equipment. For the boiling point and pressure release tests, the water samples were contained in glass test tubes. To avoid contamination from the atmosphere between pressurizing and testing, it was found necessary to seal a glass dome to the

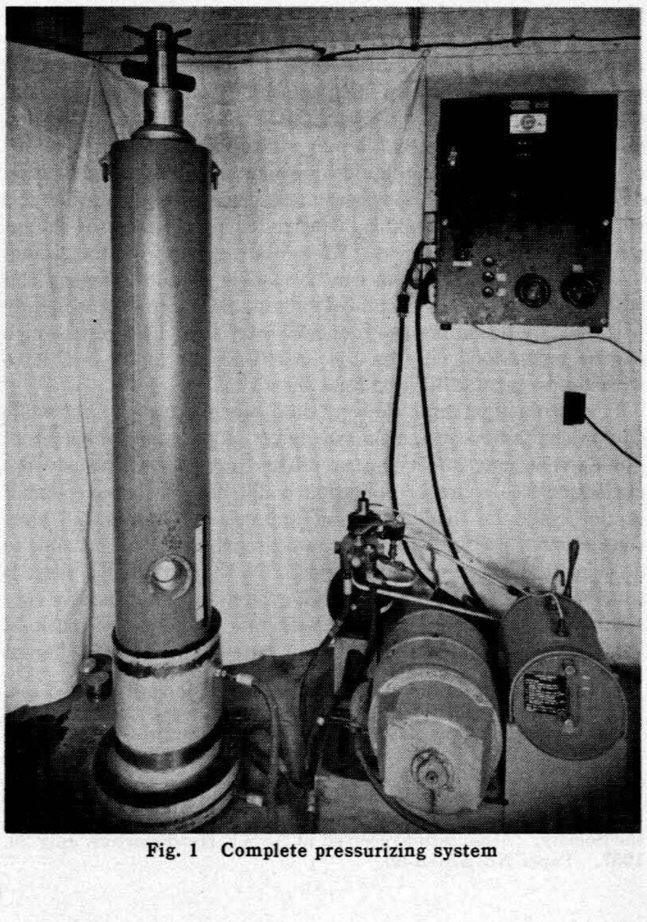

Fig. 1 Complete pressurizing system

top of each tube. This dome was vented to atmosphere by a short length of large-bore glass capillary tubing. The test tubes were approximately 6 in. long and $^3/_4$ in. in diam. Two versions are seen in Fig. 2. The open capillary insures that the pressure within the test tube is in equilibrium with the surrounding pressure while maintaining a small convectionless passage through which dust particles cannot pass into the body of the tube in the short time that it is exposed to the atmosphere. Fig. 3 shows the simple heating equipment used for measuring the boiling point of the liquid in these tubes. It was impossible to measure the temperature directly because any measuring instrument for such use must be chemically clean and inserted in the tube before pressurization. Only a metal thermocouple would withstand these pressures but this would be unsatisfactory because, even after vigorous cleaning, cavities form on metallic surfaces at very low liquid tensions. The temperature for the first cavities to appear is therefore estimated from the heating time. The apparatus is shielded from all air currents. Calibrations were run with thermocouples immersed in standard test tubes filled with unpressurized water. The rate of heating was determined from room temperature to boiling temperature. Similar calibrations were made with high-boiling-point liquids, thus carrying the temperature range up to the limits to be covered by the experiments. The equivalent heating times for water were calculated using the known specific heats of the calibrating liquids. Temperature measurements obtained in this manner are estimated to be accurate within less than 5 F. This is much smaller than the observed scatter between identical tests.

The pressure-release chamber used in the second type of static test is seen in Fig. 4. This is a small rectangular stainless-steel chamber having heavy glass windows in two opposite faces. The chamber is heated electrically on all of the metallic faces. The operating technique was as follows: A pressurized sample in a standard test tube was suspended in the center of the chamber. A small amount of water was then added and the chamber closed. The effective tensile strength of the sample was tested by opening the control valve, thus releasing the pressure of the surrounding vapor. Observations were made of the chamber pressure at the instant at which the first bubble formed in the test tube. It was assumed that during this pressure release the temperature of the sample remained constant. Since it was in its thermoequilibrium with the heated chamber walls, the effective strength of the

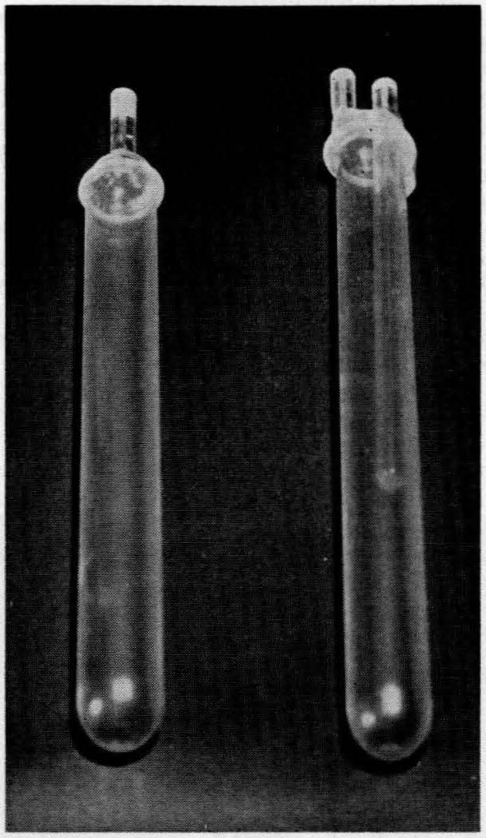

Fig. 2 Single and double capillary closed-top test tubes

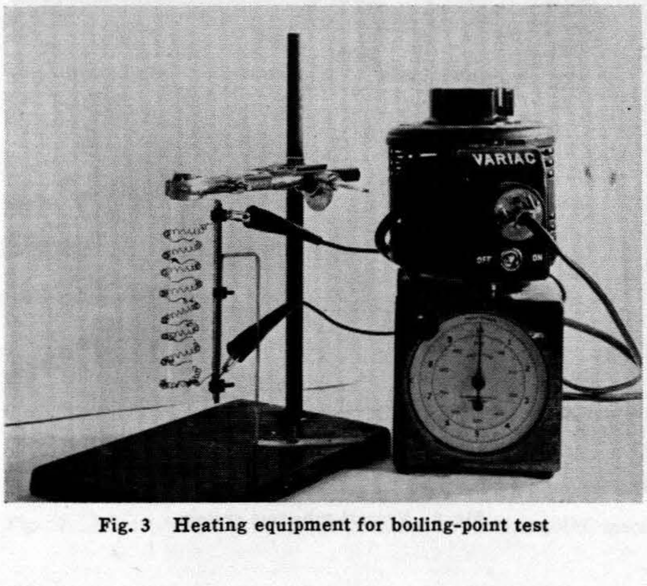

Fig. 3 Heating equipment for boiling-point test

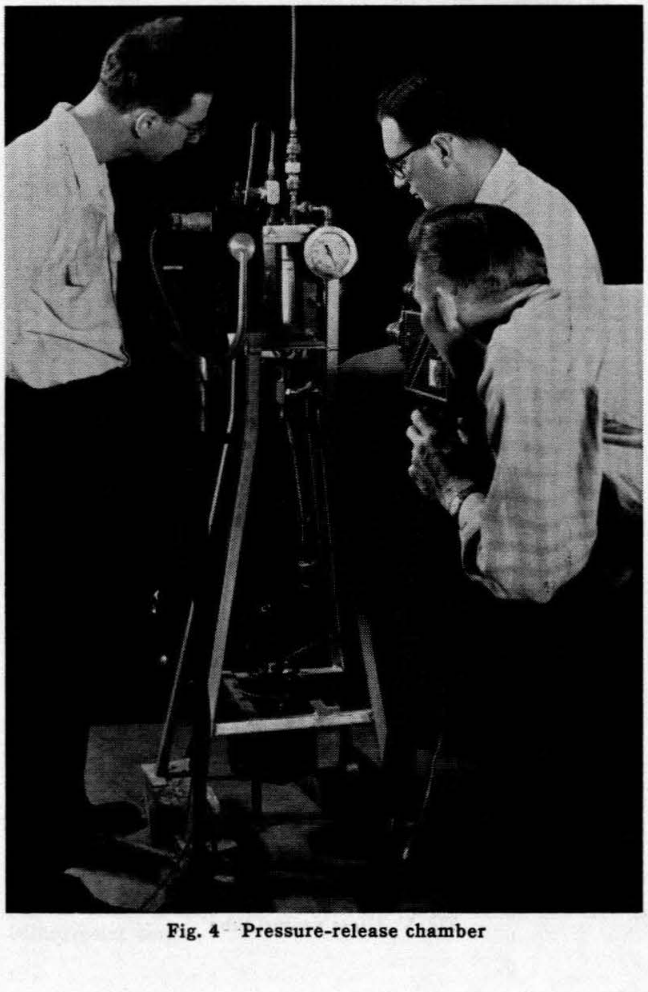

Fig. 4 Pressure-release chamber

liquid was therefore assumed to be the decrease in chamber pressure from the initial value at the instant of first-bubble formation. Two rates of pressure release were used. The fast rate was approximately 30 psi per sec. In these tests the observations were made with a motion picture camera whose field of view included both the sample and the pressure gage. In the slow release, the rate of pressure drop varied from 1 to 5 psi per sec. Here the camera was not needed since sufficient accuracy could be obtained by two observers, one watching the sample and the other the pressure gage.

Equipment for Dynamic Test. Fig. 5 shows the glass venturi tube used for this test. This tube serves as the water container, the nozzle, working section, and diffuser. Its dimensions were limited by the size of the pressurizing chamber. These tubes are of precision construction. They were made by shrinking the glass onto a stainless-steel mandrel.[3] The nozzle profile is geometrically similar to that of the High Speed Water Tunnel in the Hydrodynamics Laboratory. This insures "monotonic" pressure variations during the acceleration, with the lowest pressure occurring in the working section. A uniform velocity distribution is also obtained in the test area.

Fig. 6 shows the tube installed in the test apparatus. With it in position, the system becomes a small transient-flow water tunnel in which both the maximum velocity and the minimum pressure in the working section can be predetermined by the proper choice of the upstream drive pressure and the downstream reservoir pressure. Heating was then commenced with the control valve open. After the free water in the chamber had boiled a sufficient time to flush out all of the air with steam, the valve was closed. Continued heating caused the pressure in the chamber to rise at a relatively slow rate because of the large mass of the steel walls. During this heating cycle, the temperature of the pressurized water in the test tube lagged behind that of the surrounding stream. After the desired chamber pressure had been reached, the heat input was decreased to maintain a constant pressure for a sufficient time to insure that the temperature of the sample had reached equilibrium with that of the surrounding vapor, by the proper choice of the upstream drive pressure and the downstream reservoir pressure.

The test is started by opening a quick-acting valve between the air reservoir and the apparatus. The drive pressure builds up very rapidly, forces out the closure at the lower end of the venturi diffuser, and drives the entire pressurized sample down through the working section in the throat. The flow velocity is computed from the rate of fall of the meniscus in the constant diameter reservoir section, which forms the upper portion of the venturi tube. The pressure in the working section is determined from the calculated velocity at this point and the drive and reservoir pressures. Since both of these pressures are measured quantities, two independent calculations of working velocity can be made. They were found to agree very well. Since the length of runs was normally 1 sec or less, observations were made photographically with a high-speed motion-picture camera and Edgerton-type flash-lamp illumination. The picture-taking rate commonly used was 2000 frames per sec. This photographic record was used to de-

[3] The construction of these precision glass tubes was made possible through the interest and co-operation of Schutte and Koerting Company, and their Chief Engineer, Mr. F. Boehm.

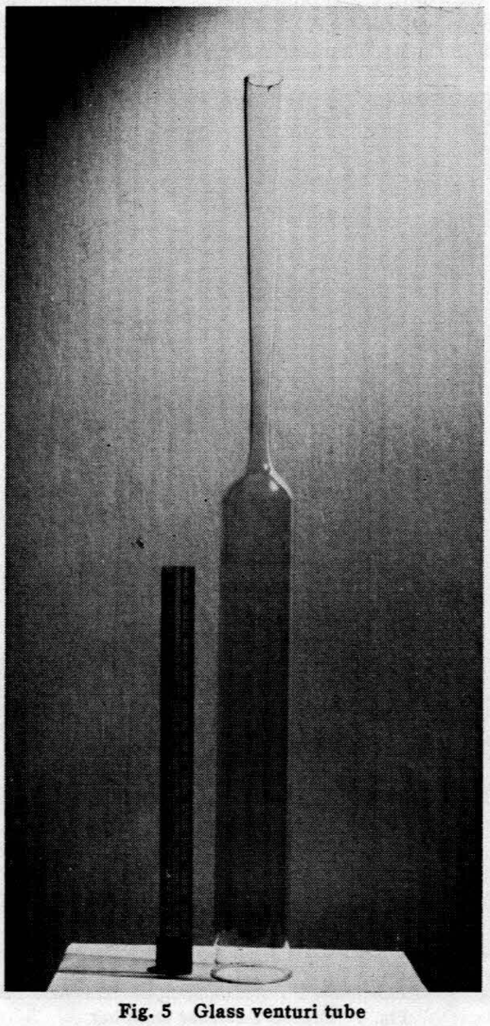

Fig. 5 Glass venturi tube

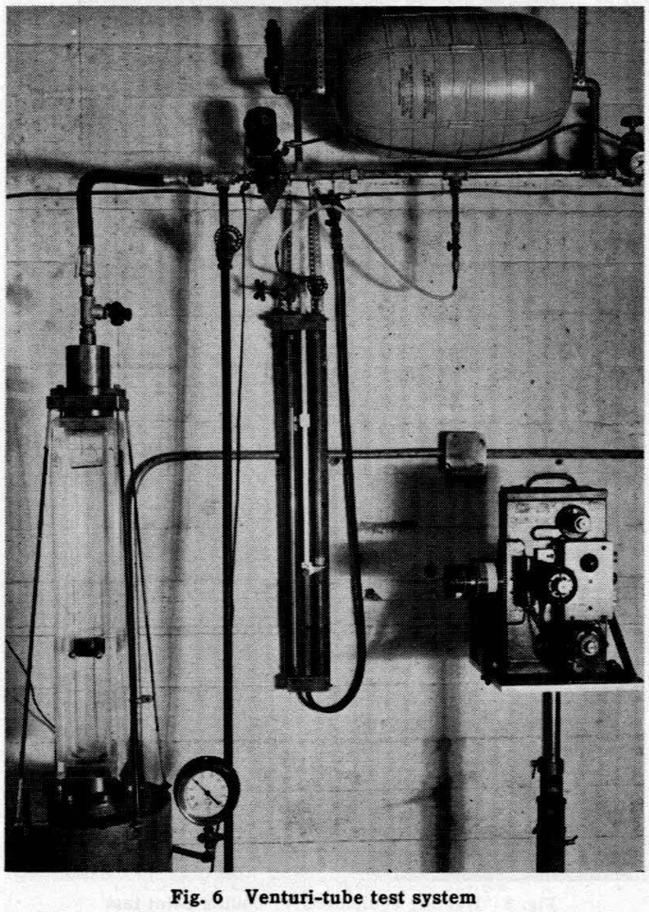

Fig. 6 Venturi-tube test system

termine both the rate of fall of the meniscus in the reservoir section and the time at which the first cavity was observed to form in the working section. Time measurements were determined very accurately by counting the number of frames on the motion pictures since the interval between frames was very precisely controlled.

Cleaning Technique. In tests of this kind if cavities originate on the surface of the container, it implies that the adhesive force between the liquid and the container surface is lower than the tensile strength of the liquid and that the latter is not being measured by the experiment. Therefore considerable time was spent in perfecting cleaning techniques which would permit the development of adhesive forces greater than the tensile stresses applied to the liquid during the tests. The techniques finally perfected proved satisfactory in that only an occasional sample was found to cavitate first at the glass-water interface. Briefly, this technique consisted in thoroughly cleaning the containers in hot chromic acid, followed by removal of the acid by copious washing with water from the same source as that to be used for the test. The significant feature of the technique appears to be that from beginning to end of the cleaning and washing process, the container surface should never be allowed to come in direct contact with the atmosphere. Whenever possible, the entire process was carried on below the surface of the liquid. Some test tubes were rejected because observation showed that in consecutive tests cavities always formed at a given spot on the surface, thus implying a fused-in impurity which could not be removed by the cleaning process.

Experimental Results

Boiling-Point Tests. In order to establish a basis of comparison of the effects of pressurization, preliminary measurements were made of the boiling point of unpressurized water using the closed top test tubes. The results were that first bubbles always appeared within a degree or two of saturation temperature for the existing barometric pressure. It was noted that these bubbles usually formed on the surface of the glass tube. Additional tests were made to try to eliminate the effect of the glass-water interface. In these tests the tubes were carefully cleaned and pressurized. They were then submerged in a bath of unpressurized water. A piece of plastic hypodermic tubing was inserted in the capillary and the pressurized water was flushed out with unpressurized tap water. Boiling-point tests with these refilled tubes gave the same results as that of the first group. The first bubbles appeared within a degree or two of the saturation temperature, but they were now observed to originate in the body of the liquid. In fact, small air bubbles were observed to appear in the body of the liquid at even lower temperatures.

The results of the boiling-point tests of pressurized water are shown in Figs. 7, 8, and 9. One general conclusion stands out immediately. Even with carefully controlled conditions, there is a very wide scatter in the test results. Some of the groups show a range of as much as 5 to 1 in the effective tensions measured under apparently identical conditions. Only a few sets of experiments show less than a 2 to 1 range. Due to the tedious nature of the experimental technique, the number of samples in each group is relatively small. It is very probable that if all of the groups had been very large, the scatter in the results would also have been uniformly large.

Fig. 7 shows the variation in the effective tensile strength of the pressurized samples as a function of the level of pressurization.

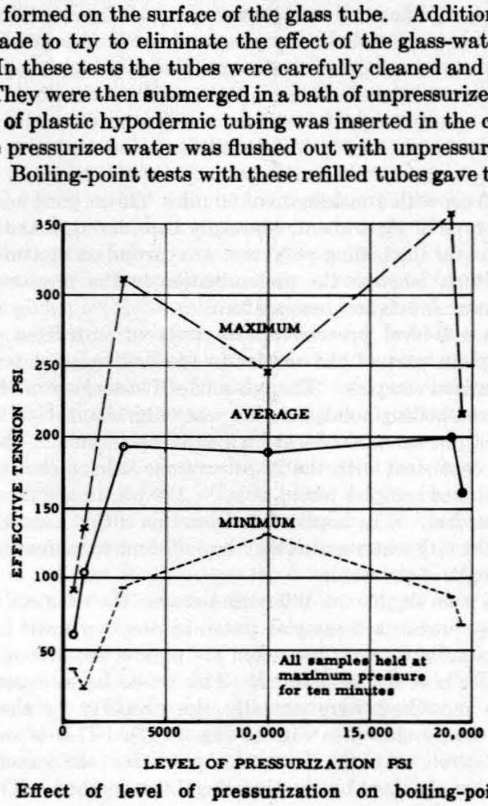

Fig. 7 Effect of level of pressurization on boiling-point tests

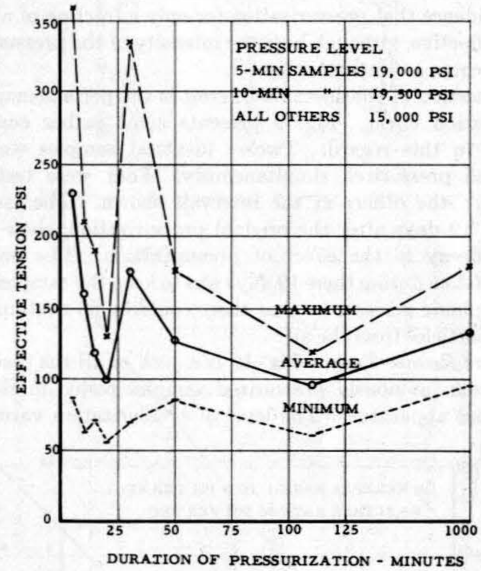

Fig. 8 Effect of duration of pressurization on boiling-point tests

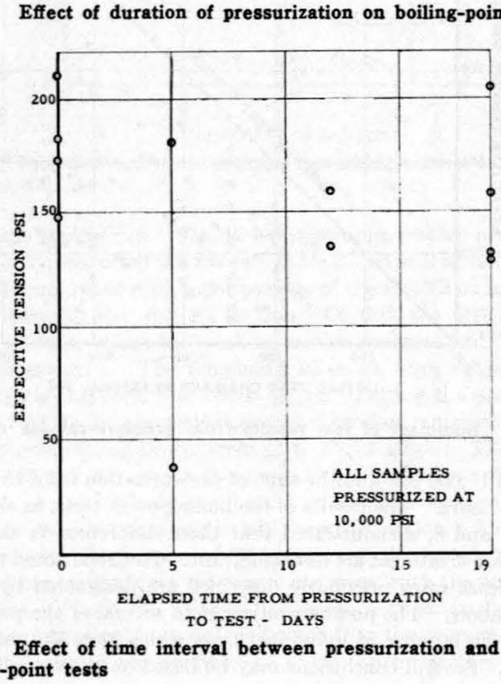

Fig. 9 Effect of time interval between pressurization and test on boiling-point tests

The time of pressurization was 10 min. Two significant conclusions can be drawn from these data. First, even the low-level pressurization of 500 psi produces a significant increase in the effective tensile strength of the water and second, pressurization above 3000 psi appears to produce no significant additional increase in effective tensile strength. Fig. 8 shows the effect of duration of pressurization on the effective tensile strength of the samples. Here the pressurization level was uniformly high, that is, near the top of the range covered by Fig. 7. The results show no significant correlation between duration of pressurization and the effective tension of the liquid. The shortest period of pressurization actually showed the highest maximum and average values, but this is quite surely a chance result due to the small number of samples in each group. The minimum duration of 5 min was controlled only by convenience in operation of the equipment. A few tests were made at a lower pressure, speeding up the entire operation as much as possible. This gave a treatment time of approximately 1 min. There appeared to be no decrease in the effectiveness of the pressure treatment. There is some indirect evidence that pressurization for only a fraction of a second may be effective, although here the intensity of the pressurization might become an important factor.

One question of considerable interest is the permanency of the pressurization effect. Fig. 9 presents some rather conclusive evidence in this regard. Twelve identical samples were prepared and pressurized simultaneously. Four were tested immediately; the others at the intervals shown. The last four, tested at 19 days after the original pressurization, show no significant decay in the effect of pressurization. The only precautions taken during these 19 days was to keep the samples sealed at atmospheric pressure so that there could be no contamination by dust particles from the air.

Pressure Release Tests. Fig. 10 is a plot of all the results obtained from previously pressurized samples tested in the pressure-release apparatus. The level of pressurization varied from

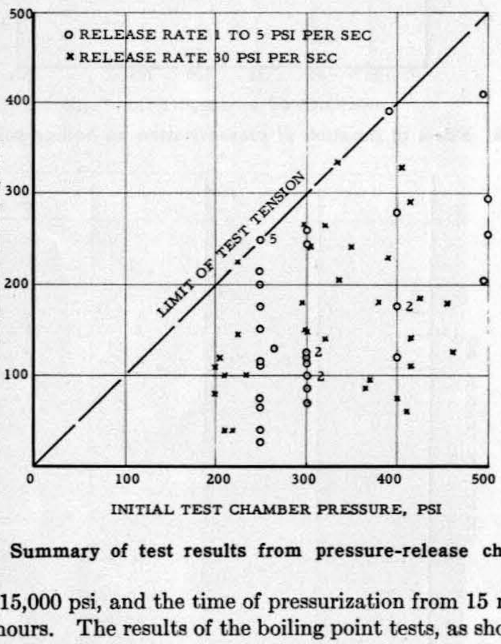

Fig. 10 Summary of test results from pressure-release chamber

5000 to 15,000 psi, and the time of pressurization from 15 min to several hours. The results of the boiling point tests, as shown in Figs. 7 and 8, demonstrated that these differences in the pressurization treatment are not significant. It will be noted that the two release rates previously described are designated by different symbols. The numbers adjacent to several of the points indicate the number of individual tests which gave the same test results. Several conclusions may be based on these results: (*a*) There seem to be no significant differences between the results obtained at the different pressure-release rates. This is rather surprising since it was assumed that the slow release rate would be a more severe test. (*b*) Although it was hoped that this apparatus would yield more consistent test results, it is seen that the scatter ratio is at least as large as it was in the boiling-point tests. (*c*) The average effective tension shown by the test seems to increase with increase of the initial test-chamber pressure.

The significance of this last result is more apparent after an examination of some auxiliary tests made in the pressure-release chamber. Two groups of samples were tested without the pressure treatment. These groups are quite similar to those used in the unpressurized tests in the boiling-point experiments. In one group the tubes were cleaned, filled, and tested without pressurization. In the second group the tubes were cleaned, filled, and pressurized, and then flushed out with unpressurized tap water. In contrast to the results from the parallel groups tested by the boiling point method, these two groups showed relatively high values of effective tensile strength. The highest result obtained with the cleaned, unpressurized tubes was 230 psi, whereas one of the tubes that had been pressurized and flushed with unpressurized water showed an effective tensile strength of 275 psi. Both of these values are higher than the average tension of the pressurized samples although, as seen from Fig. 10, many of the individual tests of the pressurized samples showed much higher values. The average tension found with 19 samples tested in clean, unpressurized tubes was 113 psi. This is in striking contrast to the 1 or 2 psi obtained in the boiling point tests. Examination showed that these 19 tests could be divided into three groups according to the pressure p_v in the test chamber at the beginning of the pressure release. Three samples have been tested at a p_v of 120 psi or lower. The average tension measured in this group was 22 psi. The 12 samples in the second group had a p_v of between 200 and 250 psi. The average tension of this group was 128 psi. The remaining four tubes had been tested at a p_v between 300 and 400 psi. Here the average tension was 136 psi. It is significant that the average tensile strength increased with p_v. It implies that the pressure-release technique inherently includes a low level pressurization at relatively high temperature, which increases the effective tensile strength of the liquid.

These results might have been anticipated from the boiling-point tests shown in Fig. 7. It will be noted that the average effective tension of the small group pressurized at 500 psi was about 60 psi with a maximum of 90 psi. This is good agreement for this type of experiment, especially considering that the pressurization for the boiling-point test was carried on at atmospheric temperature, whereas the pressurization in the pressure-release tests was at saturation temperature.

These low-level pressure-release tests of untreated samples may explain part of the scatter in the boiling-point tests with unpressurized samples. The mean effective tension of these unpressurized-boiling-point samples was only about 1 to $1^1/_2$ psi. However, one sample went as high as 47-psi tension. This value is quite consistent with the 22-psi average tension shown by the unpressurized samples tested at $p_v = 120$ psi, in the pressure-release chamber. The implication from this is that even the pressure in the city water mains may be sufficient to increase the tensile strength of the water.

There is no significant difference between the effective tensions shown by pressurized samples tested by the two static methods. The maximum tensions measured are very nearly the same, and the scatter is of the same order. This would be surprising if the tensions measured were actually the property of the liquid. This is clearly shown in Fig. 11 [fig. 1 (4)]. This is an experimental curve. At the lower temperatures the experimental points were obtained by the centrifugal test method. The water

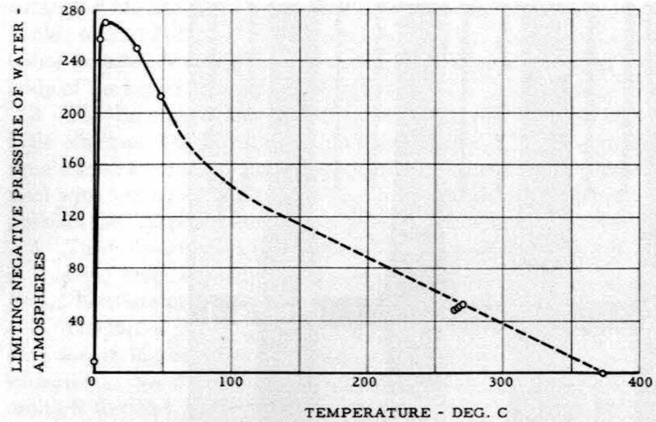

Fig. 11 Variation of limiting negative pressure of water with temperature (fig. 1 of reference 4)

used in these tests was purified by very elaborate methods to eliminate all extraneous weak points. Most of the samples tested by the boiling-point method failed at relatively low temperatures. For this temperature range the limiting tension from Briggs' curve is about 1500 psi. In the pressure-release tests the limiting p_v was 500 lb. The corresponding saturation temperature is approximately 240 C, which, from Briggs' curve, corresponds to a limiting effective tension of about 800 psi. No sample tested by either method in these experiments approached either of these values. This is conclusive evidence that the true tensile strength of the water was not being tested. Instead, the ruptures were due to the impurity weak spots.

Dynamic-Flow Tests. Two series of tests were made with the dynamic-flow apparatus. First, a group of reference runs was made with unpressurized water in the glass venturi tubes. The second group of tests was with pressurized samples. In the discussion of the results it must be remembered that there are several significant differences between these tests and the preceding ones. The basic difference is that these tests are dynamic, or flow tests, whereas the boiling-point and pressure-release tests are static, that is, the liquid is at rest. Another significant difference is that in the dynamic-flow tests each element of the liquid is tested separately as it goes through the throat, or working section, of the venturi tube, whereas in the two static tests all of the liquid elements in the sample are tested simultaneously. The size of the sample in the two types of tests is significantly different. The venturi tubes hold over 50 cu in. of liquid, whereas the test tubes used in the static tests have a volume of less than 2 cu in., thus giving a volume ratio of the two samples of over 25 to 1. One more difference needs to be mentioned. In both static tests the tension applied to the sample could be increased until it failed at the weakest point. In the dynamic test the maximum tension had to be predetermined. If too high a value was chosen, the sample might fail before equilibrium velocity was reached in the working section; if too low a value, the entire sample might flow through it without failure. Table 1 lists the results of the reference runs made with unpressurized samples. Table 2 shows the results obtained with nine runs using pressurized samples. It will be noted that in this group the drive pressures are about the same. The third and fourth columns of both tables give the pressure and the velocity in the working section at the appearance of the first cavitation bubble. The last column gives the per cent of the sample that passed through the working section before cavitation occurred. The average water temperature for both series of tests was 75 F, which corresponds to a vapor pressure of 0.43 psi. The significance of the last column needs clarification which can best be accomplished by examining in more detail the record

Table 1 Dynamic tests of unpressurized samples

Run no.	Drive pressure, psig	Throat velocity, fps	Cavitation pressure, psia	Through-flow at inception, per cent
14	4.71	51	1.33	21
15	4.22	51	1.43	25
16	3.55	50	1.20	30
17	2.98	49	0.99	50
22	4.27	51	1.24	30
23	3.83	52	0.24	35
24	3.69	52	−0.19	40

Table 2 Dynamic tests of pressurized samples

Run no.	Drive pressure, psig	Throat velocity, fps	Cavitation pressure, psia	Through-flow at inception, per cent
33	7.93	90	−32	60
34	9.05	81	−20	54
35	8.99	93	−35	72
37	9.0	64	−4	16
38	9.21	82	−21	45
39	9.15	76	−15	21
40	9.10	79	−18	28
41	9.15	95	−41	65
42	8.54	92	−34	39

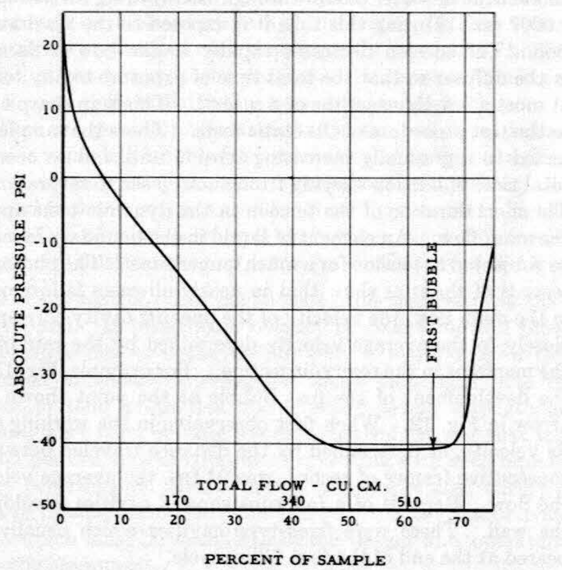

Fig. 12 Variation of absolute pressure in working section during run (Test no. 41)

of a single typical run. Fig. 12 is the pressure history of run No. 41 and is typical of all the runs in Table 2. It will be noted that the flow accelerated during the passage of the first 22 cu in. of the sample through the working section. Of this, the first 3 cu in. passed through before the working-section pressure had dropped to vapor pressure. The remaining 19 cu in. were subjected to tensions varying from 0 to about 40 psi. During the passage of the next 11 cu in. the working-section tension remained nearly constant, decreasing slowly from 41 to about 40 psi. The working-section velocity under these conditions was about 94.5 fps. The first cavitation bubble appeared when there were still 14 cu in. of the sample remaining in the reservoir section. Flow conditions during the passage of this portion of the sample through the working section were indeterminate since, with the beginning of cavitation, both the velocity and pressure fluctuated. However, the photographic records indicated that the average tension during this period was about 25 to 30 psi. After the first cavity

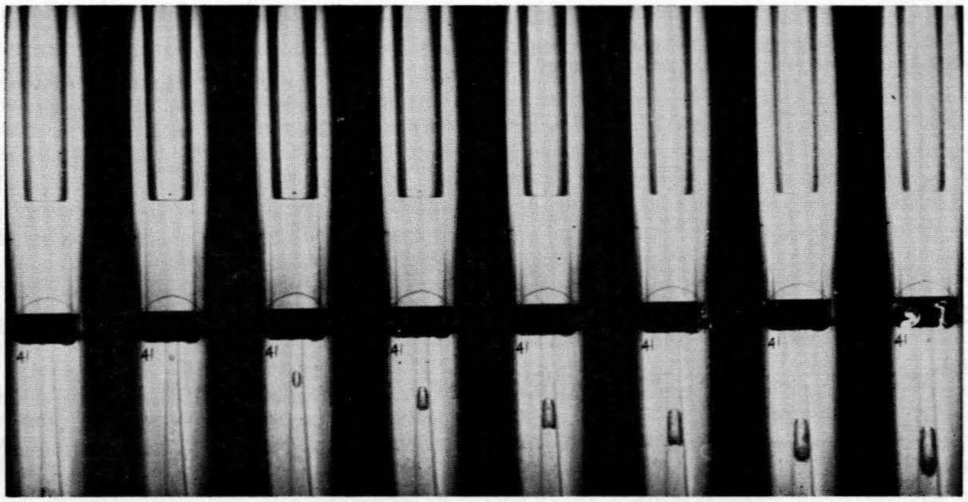

Fig. 13 Formation of first bubble during run No. 41

formed there was undoubtedly a series of relatively high pressure surges. In spite of this, only two or three new cavities formed in the working section. During the period of maximum velocity an element of water passes through the working section in about 0.0007 sec. During this time it is exposed to the maximum tension. The tension decreases rapidly as the flow is decelerated in the diffuser so that the total time of exposure to any tension is at most a few thousandths of a second. This is in sharp contrast to the test procedure of the static tests. There the sample is subjected to a gradually increasing tension until failure occurs, the total time of tension varying from about 5 sec to several minutes. The short duration of the tension in the dynamic tests applies to the main flow. An element of liquid in the boundary layer would be subjected to tension for a much longer time. The photographic records of the runs show that in nearly all cases failure occurred in the main flow, the velocity of the opening cavity corresponding closely to the average velocity determined by the rate of fall of the meniscus in the reservoir section. For example, Fig. 13 shows the development of the first bubble at the point shown by the arrow in Fig. 12. When first observable in the working section, its velocity, as determined by the distance traveled between two consecutive frames of record, was 94 fps, the average velocity of the flow. Records of a few runs showed cavities developing on the wall. These were fixed-type cavities which usually disappeared at the end of the first filling cycle.

This contrast between the results of the static and dynamic tests clarifies one characteristic of nuclei found in normal water; that is, there do not seem to be any nuclei which can resist tension for a short time before failure under the same tension if applied over a relatively long period. In other words, the growth time from nucleus to finite cavity is of the order of milliseconds or less, even for nuclei small enough to resist very appreciable tensions.

The glass venturi tubes used in these dynamic tests were very strong, and withstood for many runs the shock pressures caused by the collapse of the cavities. Fortunately, a good photographic record was obtained of one of the rare runs which terminated in a tube breakage. This record showed clearly that the time of the break coincided with that of the collapse of a large cavity.

Comparison of Results of Static and Dynamic Tests. The maximum tensions observed in the dynamic tests are about one order of magnitude lower than those obtained in the static tests. Thus it might be concluded that the tensile strength of the liquid under flow conditions was much lower than under static conditions. Such a conclusion seems premature. Both the static and the dynamic tests measure the strength of the weakest element of the liquid in the sample. In the static tests the entire volume of the sample is subjected to the maximum tension. In the dynamic test only a part of the total volume passes through the working section under tension before failure occurs. The dynamic test records show that approximately four to six times the volume of a static test passes through the working section under the maximum tension before the first bubble appears. Thus the results of one dynamic test should be compared to the minimum tension failure observed in a group of four to six static tests. It was common laboratory practice to prepare, pressurize, and test static samples in groups of six. Thirteen such groups, all of which were pressurized at relatively high levels, were re-evaluated on the basis of the minimum tension observed within each group. The average of these minimum tensions was 45 psi. The average tension of the nine dynamic tests shown in Table 2 is 26 psi. This is good agreement considering the inherently wide scatter of all of these tests. Thus it must be concluded that these experiments show no significant effect of flow on the tensile strength of water.

One limitation of these conclusions must be recognized. The flow in the working section of the dynamic test apparatus has, in all probability, an extremely low turbulence level. The monotonic design of the nozzle which is required to obviate any possibility of cavitation upstream from the throat insures smooth acceleration with no random-pressure disturbances. At the beginning of the test the liquid is at rest, and the elements that travel furthest before they reach the working section move only about eight tube diameters. Thus there is little energy available for the development of turbulence. It would be desirable to make a similar series of tests with a known turbulence level in the working section. However, this would add serious complications to the test procedure.

Summary of Results of the Effects of Pressurization and Conclusions Regarding the Properties of Natural Waters

1 The effective tensile strength of water is increased by pressurization. The amount of this increase varies with the level of pressurization, but seems to reach an upper limit at about 2000 to 3000 psi.

2 Pressures of the order of 300 or 400 psi produce definite increases in the effective tensile strength and there is some evidence that even lower pressures have a measurable effect. The most probable reason for the effects of low-level pressurization not having been commonly observed is that the solid surfaces in

contact with the liquid usually contain a plentiful supply of nuclei, so that boiling or cavitation readily takes place as soon as vapor pressure is reached, thus masking the fact that within the body of the liquid no cavities are initiated.

3 The duration of the pressurization treatment seems to have little effect on the increase in tensile strength. The treatment time varied from approximately one minute, the minimum practical with the equipment available, to several days. It is quite possible that there is a time effect for very short treatment times.

4 The pressurization effect lasts at least for weeks if the liquid is shielded from contamination with foreign nuclei during the period between pressurization and test.

5 The initial purity of the water does not seem to be a significant factor in the effective tensile strength produced by pressurization. No difference was found between the behavior of multiple-distilled water and air-saturated tap water containing relatively high concentrations of dissolved and suspended material.

6 The duration of the applied test tension in the different types of experiments varied from a few milliseconds to more than one minute. Within this range no correlation could be found between the duration of the applied stress and the tensile strength of the liquid.

7 These experiments show that normal liquids rupture or cavitate at a much lower tension than the true tensile strength of the pure liquid. These ruptures appear to occur at weak spots in the liquid caused by the presence of real nuclei which have continuing existence and specific physical properties.

8 The physical concept or "model" of the nucleus which is most consistent with the results of this series of investigations is that of Harvey: that is, a nucleus is a pocket of undissolved gas in the re-entrant crack in the surface of a solid particle of impurity which is hydrophobic to the liquid.

9 The effectiveness of nuclei as weak spots may be reduced or destroyed by pressurization. Their resistance to pressure varies greatly and is probably related both to the sharpness of the bottom of the re-entrant crack, and to the relative resistance to wetting by the surrounding liquid. The concentration of highly pressure-resistant nuclei in natural water seems to be relatively low. For example, the static test results imply that there is about one nucleus to every 2 cu in. of water whose effective tensile strength is approximately 450 psi and whose resistance to pressurization exceeds 15,000 psi, and one nucleus in each 12 cu in. whose effective tensile strength is only 15 psi but which has an equally high resistance to pressurization.

10 Weak spots which can initiate cavitation usually occur on all solid surfaces in contact with liquids. They can normally be removed from glass surfaces by rigorous cleaning methods. This implies that the weak spots are caused by hydrophobic contamination. Experiments by other investigators have shown that normal cleaning methods are inadequate to remove weak spots from metal surfaces. This is probably due to the presence of innumerable cracks or pockets which serve as hosts for free gas nuclei.

Engineering Significance of Nuclei

At this point the average engineer might well ask, "What is the significance of this information with respect to mechanical engineering?" This is a difficult question to answer at the present state of knowledge. However, it seems probable that the general properties of nuclei in liquids will be the basis for the explanation of many cases of abnormal performance of liquid-handling equipment.

Certainly the results of these experiments raise many practical questions. The following are a few examples:

1 In the operation of steam boilers is there any evidence of low-level pressurization effects which reduce the release rate of steam in the body of the liquid?

2 For the same relative velocities in cavitation areas, are low-head turbines more susceptible to cavitation than high-head turbines, both as regards its effect on performance and on degree of damage? The penstock of a high-head turbine should be an effective means of pressurization. This might not change the degree of fixed cavitation; thus the effect of the cavitation on the performance would remain unaltered. However, due to a decrease in the number of available nuclei, it might lessen the number of traveling cavities and thus decrease the relative amount of damage (10).

3 For machines handling cold water at comparable velocities, are centrifugal pumps more susceptible to cavitation troubles than high-head turbines? Here the viewpoint is the same as in the previous question. Natural waters are exposed to a continuing rain of the dust particles which serve as hosts for gas nuclei. The maximum pressurization before entering the impeller eye is measured by the submergence of the inlet pipe, which is very small compared to that in the penstock of a high-head turbine.

4 Stepanoff has pointed out that a high-pressure boiler feed pump handling hot water is less susceptible to the effects of cavitation than is the same pump handling cold water under otherwise identical conditions. He explains this by the difference in the thermodynamic properties of the liquids. However, modern boilers operate on a closed cycle with deaerated distilled water, which is highly pressurized each time it passes through the boiler. Therefore, might not at least a portion of the improved performance of the pumps be explained by a scarcity of nuclei?

5 There is a general impression that in the petroleum industry there is much less trouble from cavitation in hydraulic equipment than there is in comparable installations using water. Is it not possible that a major reason for the difference is the higher wetting ability of most petroleum derivatives, since this would tend to greatly decrease the concentration of effective nuclei?

There are a host of other questions of this general type that could be raised. In many cases detailed consideration will show that the properties of nuclei do not play a major role in the phenomenon involved. However, it seems clear that, due to variations in their properties, the effective tensile strength of liquids may vary from nothing to quite high values, and that the cavitation performance of equipment operating with such liquids will vary accordingly. Hence nuclei, and the related effective strength of liquids, form one more facet of the cavitation phenomenon which must be considered in the design and operation of hydraulic equipment.

Acknowledgments

The support for these investigations came from research contracts with the Bureau of Ordnance and with the Mechanics Branch of the Office of Naval Research. The experiments were performed by two research assistants, Nathan Gainsboro and Frank Bonamassa. They contributed much to the development of satisfactory techniques and the analysis of the results, in addition to the tedious work of the tests themselves.

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Discussion

L. J. Briggs.[4] In the writer's opinion, cosmic radiation may be responsible in part for the low and widely scattered values obtained in cavitation measurements. Glaser[5] has shown that, when a highly energized cosmic ray passes through a superheated liquid, bubbles are formed and the liquid explodes. The probability of such an event is proportional to the product of the maximum cross section of the exposed liquid and the time of exposure.

In the writer's measurements of the maximum negative pressure developed in superheated water (see Fig. 10 of the paper), the maximum exposed area of the liquid was only 0.6 sq cm and the exposure time 5 sec. The probability that an energetic cosmic ray would pass through this area during this time is of the order of only 1 part in 1000. But here the area and time of exposure were kept near a minimum, and in most setups the probability would be much greater.

The most striking feature of the cavitation of water is the remarkable change in cohesive strength which occurs near the freezing point. The highest value observed by the writer for the limiting negative pressure (cohesive strength) of water was about 270 atm (4000 psi) at 8 C, Fig. 10. From here it drops steadily but precipitously to only 7 or 8 atm at its freezing point. Some other liquids which the writer has measured show a slight drop as their freezing points are approached, but nothing compared with this 35-fold change.

[4] Director Emeritus, National Bureau of Standards, Washington, D. C. Mem. ASME.

[5] D. A. Glaser, "Some Effects of Ionizing Radiation on the Formation of Bubbles in Liquids," *Physical Review*, vol. 87, 1952, p. 665; "Bubble Chamber Tracks of Penetrating Cosmic-Ray Particles," *Physical Review*, vol. 91, 1953, pp. 762–763.

The foregoing measurements were made by a centrifugal method.[6] The water was contained in a capillary glass tube, open at both ends, the tips being bent back to form a nearly closed Z. When the capillary was mounted symmetrically on its spinner and filled so that both short legs contained water, the system was dynamically stable at any speed. The open ends of the tube made it easy to clean and fill. The greatest difficulty the writer has experienced is the breaking of the capillary tube when the water column, under high stress, suddenly ruptures at its center and impacts against the curved ends of the tube.

K. F. Herzfeld.[7] In the problem of cavitation, many contradictory experimental results appear in the literature and therefore reliable experiments are very valuable. The necessity for the presence of "nuclei" as weak spots is now generally recognized, but there is no agreement as to their nature. The experimental methods fall into three goups: Pressure release, start of boiling, use of ultrasonic waves. The increase in tensile strength of the liquid due to previous pressurizing found by the author occurs also in ultrasonic tests, but much lower pressures (15–100 psi) are effective there.[8,9] The interesting comparison of tensile strength in flow tests and static tests—comparing application times of milliseconds and of minutes without apparent effect on strength—agrees with the ultrasonic experience according to which cavitation pressure is independent[10] of frequency up to 10 kc.

E. G. Richardson[9] has also discussed the persistence of the nuclei.

One of the most valuable results of the paper, at least for the writer, is the estimate of the number of nuclei.

Some recent experiments of Liebermann[11] on the nature of nuclei should be mentioned.

Author's Closure[12]

In connection with Dr. Briggs' discussion, it is interesting to note that in discussing the effect of pressurization of water in a recent report,[13] Professor Knapp considered the effect of cosmic rays. His conclusion in this regard is as follows:

"No correlation was found between the average tensile strength at failure and the duration of the tension even though this duration varied over several orders of magnitude between the different tests. This result implies that cavity formation in liquids under tension cannot be explained by nucleation resulting from cosmic rays or other high energy radiation received by the liquid while under tension."

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[7] Department of Physics, The Catholic University of America, Washington, D. C.

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[11] L. Liebermann, "Air Bubbles in Water," *Journal of Applied Physics*, vol. 28, 1957, p. 205.

[12] Written by Dr. Vito A. Vanoni, Professor of Hydraulics, California Institute of Technology, due to the sudden death of Professor Knapp on November 7, 1957.

[13] "Investigation of the Mechanics of Cavitation and Cavitation Damage," Final Report, ONR Contract Nonr-220(08), dated June, 1957. Conclusion 6, p. 35.